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WEAR OF DIES FOR EXTRUDING PLASTIC CLAY

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ABSTRACT

Dies of 21 materials were investigated and the following determinations made: approximate taper or "angle of wear" of the dies necessary to produce constant wear losses, relation between wear loss and extrusion pressure, relative service values, Vicker's hardness numbers, the decrease in wear resistances of nitrided steel and porcelain due to their hard outer portions, and the relative abrasive intensity of a plastic porcelain body as compared to that of a plastic clay-sand mixture.

The angle of constant wear rate was found to be approximately 3.58°. The relative service values ranged from 3.22 for a soft brass to 1,673 for an alloy composed of cobalt, chromium, and tungsten. The wear resistance of porcelain decreased asymptotically with depth, and the wear resistance of nitrided steel varied irregularly as successive layers of the case were removed by abrasion. There was no correlation between service values and Vicker's numbers for unlike materials, but there was, in general, a direct relation between the two properties for materials of the same kind. The relative wear loss of any one material is equal to the 1.548th power of the extrusion pressure divided by a constant.

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I. INTRODUCTION

In the "stiff mud" process for manufacturing clay products, the clay in the stiff plastic condition is extruded through a die from which the clay issues in the form of a continuous bar or column which is then cut by wires into proper lengths for brick, tile, porcelain tubes, or whatever product is being made.

Most clays are highly abrasive in character, causing rapid wear of the dies so that frequent renewals are necessary in order to maintain uniformity in size of product. The predominating abrasive material in clays consists of quartz grains or silica sand, of which from less than 1 percent to more than 50 percent may be present.

No data were available regarding the wear resistance of dies to plastic clay and it was for the purpose of obtaining such data that this investigation was undertaken.

The laboratory tests were made in a manner to simulate practical working conditions. The materials were made in the form of dies and a definite volume of clay was forced through the dies during each test at a constant volume rate. With a new die the length of clay column produced per unit of time was equal to the length of column from an auger machine producing approximately 7,000 side-cut face brick per hour.

II. MATERIALS INVESTIGATED

1. TYPE AND HISTORY

The most commonly used materials for dies in the clay industry are cast iron and high carbon steel, both comparatively inexpensive. Specimens of these materials and also others not so commonly used were included in the investigation. The materials included were 1 brass, 1 copper, 4 cast irons, 3 stainless steels, 5 differently heat-treated specimens of a chromium tool steel, 1 high carbon steel, 1 chromium-molybdenum steel, 3 chromium-cobalt-tungsten alloys, 1 nitrided steel, and a porcelain.[1] The chemical composition and history of each specimen are given in table 1.

[1] Chromium-plated cold rolled steel dies were also included. The plating wore through in spots, "chipping" followed, and no satisfactory value was obtained.

TABLE 1.—*Chemical composition, source, and heat treatment of dies investigated*

Specimen no.	Graphitic C	Total C	Cr	Mo	Co	Mn	Ni	W	Al	Si	P	S	Remarks
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	
3	--------	1.50	12.50	1.10	0.60	0.50	0.20	--------	--------	0.30	--------	--------	Chromium-molybdenum steel. Dies made by the manufacturer. Mill analysis.
4	--------	.30	1.09	.24	--------	.54	.12	--------	0.91	.56	0.02	0.02	Nitrided steel. Dies made by the manufacturer, and nitrided for 48 hours at 975 F by Dr. Victor O. Homerberg, division of physical metallurgy, Massachusetts Institute of Technology. Analysis by chemistry division, Bureau of Standards.
5	3.26	3.95	--------	--------	--------	.71	--------	--------	--------	2.85	.79	.03	Cast irons. Dies machined from castings made by the metallurgical division and analyses by the chemistry division, Bureau of Standards.
6	3.12	3.72	--------	--------	--------	.57	--------	--------	--------	2.24	.46	.08	
7	2.95	3.57	--------	--------	--------	.24	--------	--------	--------	2.80	.83	.02	
8	2.86	3.73	--------	--------	--------	.18	--------	--------	--------	1.63	.49	.02	
11	--------	--------	35	--------	50	--------	--------	10	--------	--------	--------	--------	Cobalt-chromium-tungsten alloys. Dies and "type composition" supplied by the manufacturer. Nos. 12 and 13 were cast by different methods which were not revealed.
12	--------	--------	30	--------	50	--------	--------	15	--------	--------	--------	--------	
13	--------	--------	30	--------	50	--------	--------	15	--------	--------	--------	--------	
14	--------	.12	12.22	--------	--------	--------	.24	--------	--------	--------	--------	--------	Stainless steels. Dies made by the manufacturer. No. 15, annealed. No. 16 hardened by rolling. Mill analyses.
15	--------	.09	18.46	--------	--------	--------	8.83	--------	--------	--------	--------	--------	
16	--------	.09	18.46	--------	--------	--------	8.83	--------	--------	--------	--------	--------	
17	--------	1.00	--------	--------	--------	2.90	--------	--------	--------	.13	.02	.02	High-carbon steel. Dies made from stock (S.A.E. 1095). Mill analysis. Dies heated to 1450 F, quenched in water and tempered to 500 F. Heat treatment by metallurgical division, Bureau of Standards.
19	--------	.97	3.90	--------	--------	.20	--------	--------	--------	.37	.02	.02	Chromium tool steel. Dies made and heat treated by a manufacturer of porcelain. Mill analysis. Heat treatment: no. 19, annealed; no. 20, heated to 1050 F and hardened in air blast; no. 21, heated to 1650 F and hardened in air blast; no. 22, heated to 1750 F, hardened in air blast and drawn to 750 F; no. 23, heated to 1750 F, hardened in air blast and drawn to 1150 F.
20	--------	.97	3.90	--------	--------	.20	--------	--------	--------	.37	.02	.02	
21	--------	.97	3.90	--------	--------	.20	--------	--------	--------	.37	.02	.02	
22	--------	.97	3.90	--------	--------	.20	--------	--------	--------	.37	.02	.02	
23	--------	.97	3.90	--------	--------	.20	--------	--------	--------	.37	.02	.02	

	Cu	Zn	Ni	Mn	Fe	Sn	Al	Pb	
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	
9	99.80	--------	--------	--------	--------	--------	--------	--------	Copper. Dies machined from electrolytic copper cast by the metallurgical division, Bureau of Standards. Approximate analysis.
10	49.70	45.14	1.95	1.33	0.97	0.60	0.22	0.11	Brass. Dies machined from a piece of ship propeller blade of German origin. Analysis by chemistry division, Bureau of Standards.

	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5	
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	
24	49.60	45.20	1.85	1.20	0.54	0.16	0.80	0.08	0.55	Porcelain. Dies and approximate analysis supplied by the manufacturer.

(a) NITRIDED STEEL

Photomicrographs of nitrided steels [2] have shown that their cases are composed of distinct layer-like parts corresponding to different degrees of hardness according to the hardness numbers. This indicated that variable wear would be encountered with depth of material removed as wear progressed, and the nitrided steel was, therefore, included for a study of its wearing behavior.

(b) PORCELAIN

In a certain factory the dies for extruding spark plug blanks were made of chromium tool steel. In searching for a more serviceable die material a die was made of the spark plug body and heated in the kiln with the regular product. The die was given a service test in comparison with the steel die. The latter, producing 30,000 blanks a day for 35 days, had extruded approximately 66 miles (103.8 km) of material and had enlarged 0.016 inch (0.406 mm). The porcelain die, used for 85 days, had extruded approximately 160 miles (275.5 km) of material and had enlarged 0.020 inch (0.508 mm). Two unglazed dies of the same porcelain as the experimental plant die were submitted by the manufacturer for tests.

The porcelain dies were formed by molding, in the plastic condition, drying and machining to size, making proper allowance for shrinkage during heating. The machining removed the original surface of the dry porcelain body and, therefore, the factors set forth by Navias [3] as being responsible for the so-called "skin" were eliminated. The porcelain was included for the purpose of determining its wearing behavior and also whether a skin not ascribable to the finishing process was developed during the heating process and, if so, whether its presence would be indicated by changes in wear resistance with depth.

III. EQUIPMENT AND TEST METHODS

1. DIES

(a) FACTORS INFLUENCING WEAR

For a definite volume of clay extruded under constant working conditions, the wear depends upon the amount of abrading area of the clay contacting and sliding over the working face of the die and the pressure under which that area is acting. The greater the magnitude of either of these two factors, the greater is the wear. Inasmuch as the pressure which is greatest at the die entrance drops as the clay passes through the die, the wear is greatest near the orifice [4] entrance and diminishes toward the exit.

For a definite volume of clay extruded the area of the clay passing any transverse cross section of a cylindrical orifice is obviously the same. As the orifice entrance enlarges in wearing from the cylindrical

[2] Trans. Am. Soc. Steel Treating, vol. 16, no. 5, 1929, Nitriding Edition.

[3] "During the molding, finishing and drying processes, the very fine particles of materials are brought to and rubbed over the surface, and in the firing process they form a vitreous skin, often more vitreous than the interior of the specimen"; Metal porosmieter for determining the pore volume of highly vitrified ware, Jour. Am. Cer. Soc., vol. 8, no. 12, p. 818, 1925.

[4] In this report the term "orifice" designates the opening through the die.

toward the tapered form, the abrading area of a definite volume of the clay increases as it passes through the orifice, thus tending to increase wear, but at the same time it is acting under diminishing pressure. When a certain balance occurs between the actions of increasing wear due to increasing clay area and decreasing wear due to decreasing pressure as the clay passes through the die, then that taper or "angle of constant wear rate"[5] has been developed where a layer of substantially uniform depth is removed.

(b) DEVELOPMENT OF TAPERED ORIFICE AND RELATION BETWEEN WEAR RATE AND TIME EQUIVALENT IN WEARING FROM CYLINDRICAL TO TAPERED FORM

In the preliminary work the dies were made with cylindrical orifices ¼ inch (6.35 mm) in diameter and 1-inch long (25.4 mm). The wear loss was small at first, increasing with successive tests and apparently approaching a constant value. During the first test the wear was confined close to the die entrance and, in successive tests, gradually approached the exit. With a cast-iron die (no. 2) of unknown composition, the exit end of the orifice showed no increase in diameter until the fifth test, when a very small increase was observed.

Figure 1, representing a longitudinal cross section of the die and protecting ring,[6] illustrates the manner in which the wear progressed. The curves represent approximately the outlines of consecutive portions removed, the decreasing curvature suggesting that wear was progressing toward some definite form of tapered orifice. The wear losses of the last four tests were approximately in agreement and the angle of taper, determined by micrometer measurements of plaster casts, was found to be 3.55°.[7]

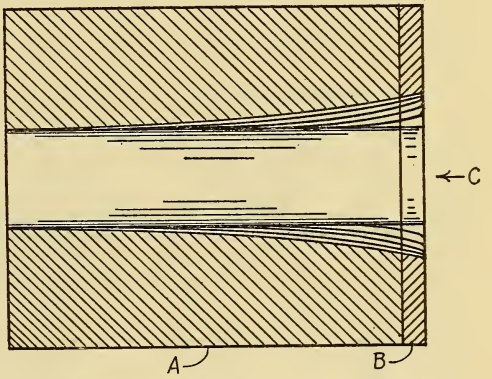

FIGURE 1.—*Cross section of a cast-iron die showing approximately the progression in wearing from an orifice of cylindrical form toward a tapered orifice of constant wear rate.*

A, die; B, protecting ring; C, entrance.

In figure 2 the relative wear rate[8] is plotted against the number of the test, which is equivalent to plotting against units of time inasmuch as each test required substantially the same time (32 ± ⅛ minutes). The relation between relative wear rate and time equivalent in wear-

[5] The angle of constant wear rate may be affected by the presence of local soft and hard spots in the die material. Where one solid is rubbing against another, the hard spots tend to shield the soft ones from wear. But plastic clay when flowing under pressure exhibits more of the properties of a liquid than it does of a solid and in moving over the die surface the clay wears the soft spots more rapidly than the hard ones; thus surface irregularities may be developed. Also, it has been observed in dies under factory conditions that when a scratch or groove occurs in the die, instead of smoothing out under continued wear it generally grows wider and deeper.

[6] Each die was provided with a protecting ring of the same material which was placed at the entrance end of the die to protect it from wear so that the measured wear would be confined to the die orifice. The protecting ring was located in the same relative position as the "die plate" or "bolting plate" of factory-operated dies.

[7] The measurements were made to the nearest 0.0005 inch; hence the results are accurate to approximately ±0.03°.

[8] Relative wear rate is defined on p. 511.

ing from cylindrical form to the taper of constant wear rate is of the form:

$$(a+u)\ (b-v)=R$$

in which u is time equivalent, v is relative wear rate, and a, b, and R are constants. The values obtained for these constants which conform closely to the data are:

$$a=2.473,\ b=0.04568,\ R=0.113$$

Theoretically, the value of the asymptote $v=b=0.04568$, represents the constant wear rate of the die. Evidently the die when measured

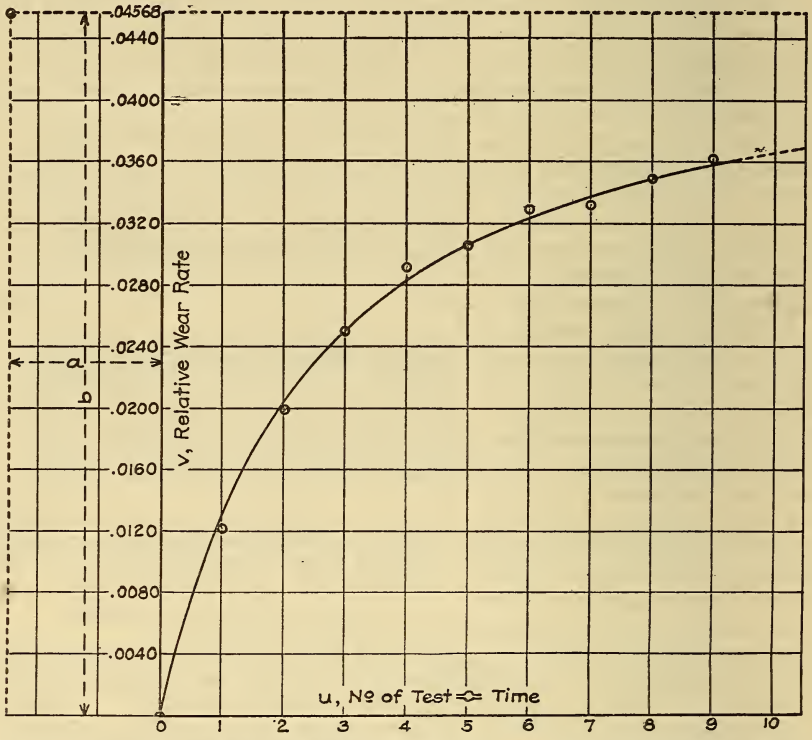

FIGURE 2.—*Relation between relative wear rate v and time equivalent u for cast-iron die no. 2 in wearing from the cylindrical orifice toward the tapered orifice of constant wear rate.*

after the ninth test had not attained the angle of constant wear rate. Theoretically, this would require that the die be operated under constant conditions for an infinite time.

(c) ANGLE OF ORIFICE ADOPTED FOR TEST DIES

It was desirable that the orifice of the die specimens be made to such a taper as would give wear losses comparable within the inherent errors of measurement. Therefore, 8 dies consisting of 2 each of the brass, cast irons nos. 5 and 6 and stainless steel no. 14 were made with tapered orifices of 3.58° [9] and when subjected to the wear tests pro-

[9] This taper can be formed with a stock reamer.

duced results for each die within close agreement. Therefore, the dimensions of the orifice as shown in figure 3 were adopted for all the test dies.

To determine whether the original taper of 3.58° had changed significantly during the tests, plaster casts were made of 14 dies which had shown high-wear losses. The angle to which each die had worn was determined from the average of eight measurements. The maximum angle calculated from the measurements was 3.85°, the minimum 3.43° and the average 3.66° or 0.08° greater than that of the angle to which the dies were originally made.

2. EXTRUSION APPARATUS

A screw-power beam and poise testing machine, capacity 20,000 pounds, was used for extruding the clay, the set-up for a test being shown in figure 4. The extrusion cylinder of the press was made of 6-inch wrought-iron pipe bored and fitted with a hard brass piston machined to a neat sliding fit. The piston was actuated by a detachable push rod and the upper, or exit end, was provided with a flange to which a removable head was bolted. A removable brass capsule was provided for holding the die and protecting ring, the capsule being threaded to fit into the center of the head.

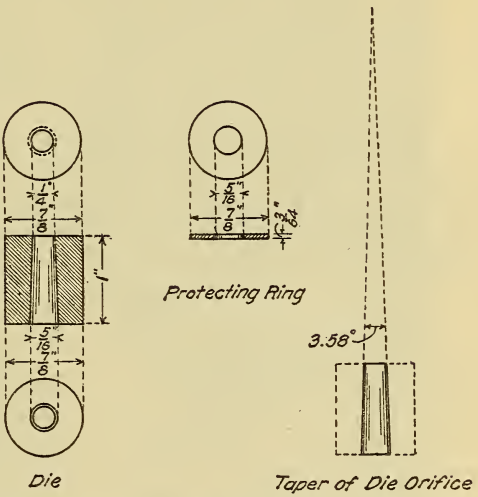

FIGURE 3.—*Dimensions of the die and protecting ring.*

The extrusion press was placed in the testing machine with the die exit upward. The push rod and piston remained stationary and the movable head of the testing machine carried the cylinder downward. The length of clay column extruded was determined by a measuring wheel and counter.

3. ABRADING MEDIUMS

Two abrasive mediums designated as clay no. 1 and clay no. 2 were used in making wear tests. Clays as prepared for the stiff mud process of manufacture generally lack uniformity in fineness of grain, plasticity, and amount and distribution of abrasive grains. They can, however, be made substantially uniform in particle distribution and working properties by repeated tempering and extrusion through a die.

(a) SELECTION OF CLAY NO. 1

A plastic Maryland clay was selected as the basis for preparing clay no. 1. The characteristics of the Maryland clay concerning fineness

of grain and plasticity were very similar to those of a ball clay. It had been used in a previous investigation [10] in which it had been repeatedly tempered and extruded from the die of a stiff mud auger brick machine and therefore it was thoroughly mixed and substantially constant in behavior.

In the preliminary tests this clay caused so little wear on the dies that it was necessary to produce larger and more conveniently measurable wear losses. Inasmuch as silica sand is the most predominant abrasive material of clays, a comparatively fine-grained glass sand was added to increase wear. Its sieve analysis is given in table 2.

TABLE 2.—*Sieve analysis of sand used in preparation of the abrasive clay no. 1*

U.S. standard sieve	Retained
Number	*Percent*
20	00.0
40	27.6
60	90.5
80	95.8
100	97.5

Preliminary tests indicated that a mixture of 60 parts clay and 40 sand, tempered with water to the stiff mud condition was satisfactory for the intended purpose. It was sufficiently plastic to flow well through the die, its abrasive intensity was approximately five times that of the Maryland clay alone, and it is hereinafter referred to as "clay no. 1."

(b) PREPARATION OF CLAY NO. 1

Sufficient quantities of the air-dry clay and sand were thoroughly mixed and stored in a closed bin. To obtain a satisfactory stiff mud consistency, batches of the mixture were tempered with different additions of water. It was found that the addition of approximately 14.8 percent by weight of the air dry clay-sand mixture produced the proper consistency. It developed, during the preliminary tests, that the extrusion pressure could not be maintained constant from day to day or from one test to another even though a definite amount of water had been added to the clay-sand mixture. The major cause [11] of this variation was apparently differences in evaporation with changes in relative humidity. A variation in extrusion pressure of as much as 8 percent was observed between days of very high and days of very low humidity. Inasmuch as extrusion pressure could not be maintained constant and since wear increased when extrusion pressure increases, it was necessary to determine the relation between extrusion pressure and wear so that the wear losses could be reduced to a comparable basis.

The earlier tests were made with a variation in water content from 14.7 to 15 percent which together with the uncontrollable factors, produced differences of 18 to 28 percent in extrusion pressure. This range of water content was selected to keep the limits of the tempered mass within the practical working range of stiff mud clay. However, it was later thought desirable to use a wider range of

[10] P. C. Grunwell, Studies of Machines for Extruding Clay Columns. Augers, Spacers, and Dies, B.S. Jour. Research, vol. 1 (RP 36), pp. 1023–1057, 1928.

[11] Enlargement of the die orifice and frictional resistance of the die material to flow of the abrasive also are influencing factors. This was especially pronounced in the case of the copper dies.

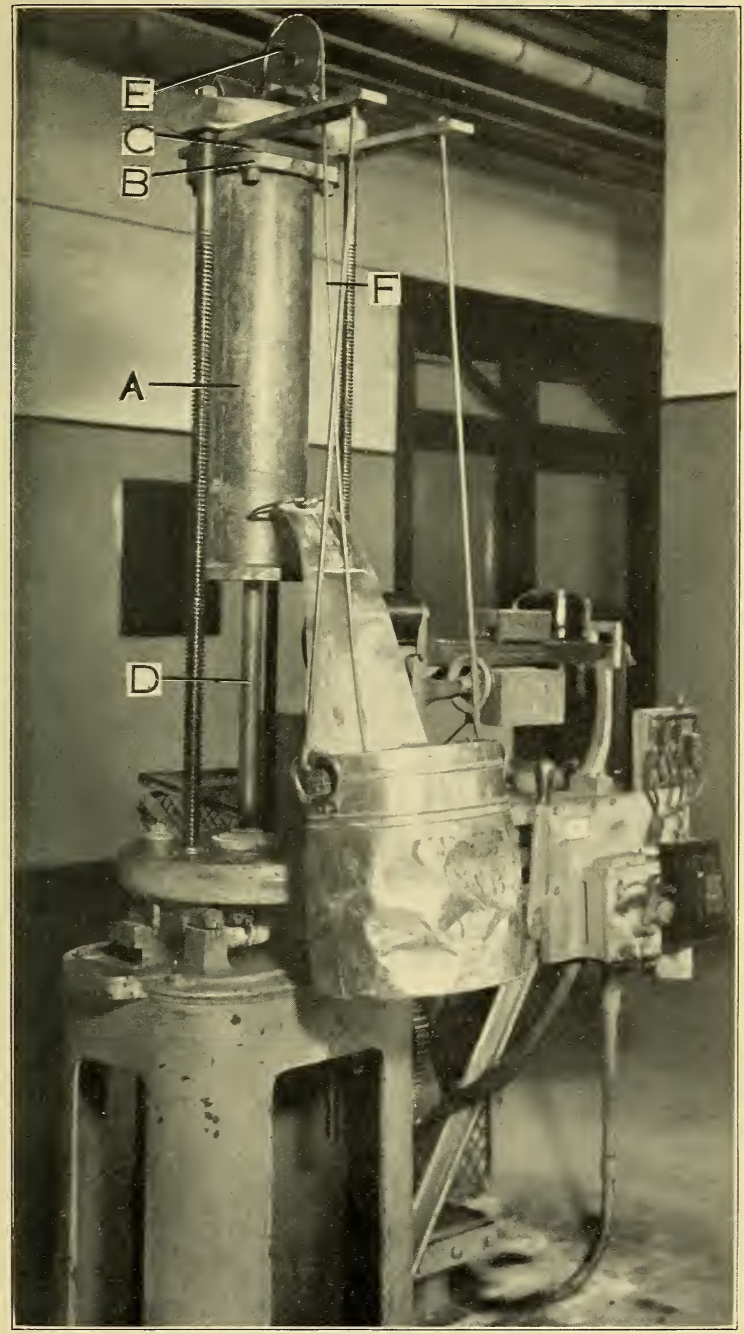

FIGURE 4.—*Complete assembly for wear tests showing the extrusion press in place in the testing machine.*

A, Cylinder; B, flange; C, head; D, push rod; E, measuring wheel; F, clay column

extrusion pressures to obtain a greater spread of the data, even though it would require that the clay be tempered to a consistency too stiff at one end of the range and too soft at the other for a commercial working stiff mud clay. Preliminary tests indicated that the addition of 14.36 to 15.05 percent water for tempering produced about the maximum range of workability. The difference of 0.69 percent water content together with the uncontrollable factors affecting pressure produced a variation in extrusion pressure of 33 to 50 percent.

(c) CLAY NO. 2

A porcelain body used as the abrasive to determine its abrasive intensity in comparison with that of clay no. 1 was received in the air dry condition from the manufacturer of the porcelain dies. It was substantially of the same composition as the mixture from which the dies had been made and it had been ground sufficiently fine to pass a no. 180 sieve.

In the preliminary tests to determine the proper water content for the desired range of stiff mud consistency, it was found that from 33 to 35.5 percent water by weight of the air dry material was required. The porcelain body in the plastic condition is hereinafter called clay no. 2.

(d) TEMPERING PROCESS

Clays nos. 1 and 2 were tempered by mixing the proper weights of the air dry material and of water required for each test. The tempering was done in a closed pug mill to lessen evaporation and 30 minutes was ample to insure thorough tempering and uniform consistency.

4. TEST PROCEDURE

(a) EXTRUSION

The tempered mass was removed from the pug mill in small portions at a time and thoroughly tamped into the extrusion cylinder. When the cylinder was full the top was leveled off and the head bolted in place. The die to be tested and its protecting ring were placed in the retaining capsule and the capsule inserted in the head. The cylinder was immediately placed in the testing machine and the extrusion made at a constant rate of piston displacement.

The time required to complete an extrusion was $32 \pm \frac{1}{6}$ minutes and the piston load readings were made at half-minute intervals during the total piston travel of 19 inches (48.26 cm), leaving a cake 1¼ inches (3.175 cm) thick between the piston and cylinder head. The average length of clay column extruded was 875 feet (266.7 m).

After the initial increase during the first 2 or 3 minutes, the load remained constant within about ±150 pounds (±68.04 kg) until about the 27th minute, when the close approach of the piston to the head caused the load to increase. A typical plot of the load against piston travel (also time) is shown in figure 5. The approximately horizontal part of the curve obviously corresponds to working conditions with constant feed and the average load over this part of the travel was considered as representing what would happen under such conditions. This average load expressed in kg/cm^2 of piston area will hereinafter be referred to as the "extrusion pressure" and denoted by p.

(b) AVERAGE DIAMETER AND AREA OF CLAY COLUMN

The average diameter of clay column and its area were calculated from the length of column and the constant volume extruded. The length of extruded column decreased 0.3 percent during three tests of the most wear-resistant dies and 40 percent approximately for three tests of the least wear-resistant dies.

(c) WEAR LOSS AND DEPTH OF WEAR

The die was weighed to one tenth of a mg before and after the test and the difference representing the wear was expressed in mm ^{3}.

The depths, or thicknesses, of the layers of material removed by wear from the nitrided-steel and the porcelain dies were determined indirectly. This method depends upon the assumption that the

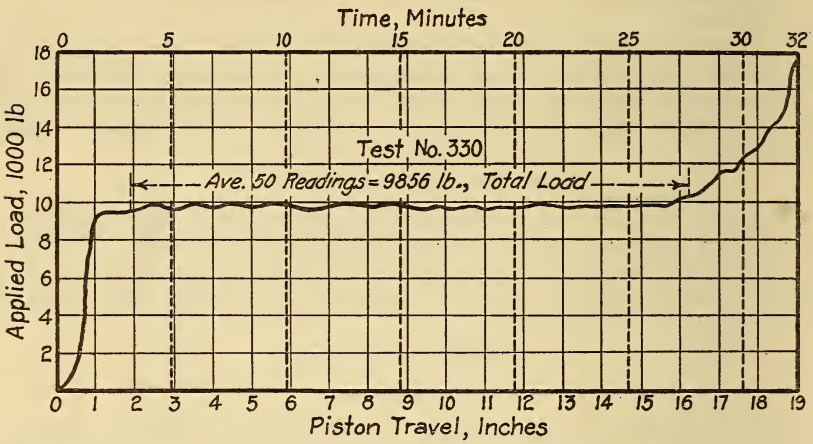

FIGURE 5.—*Relation between piston load and piston travel during a wear test.*

difference between the average diameter of the clay column of one test and that of another is equal to twice the thickness of the layer removed from the die by wear when the die has an angle of constant wear rate. This method of determining depth proved to be more sensitive and consistent than measurements by either a plug gage or an optical micrometer.

IV. RESULTS

1. WEAR COEFFICIENT

As the orifice of the die was enlarged by wear, the length and surface area of a given volume of the clay column decreased, hence the effective abrading area of the clay decreased. Obviously the wear of successive tests of a die, or tests of different dies, must be reduced to a common basis to be comparable.

Analysis of the data from more than 200 tests indicated that the wear for any one material was directly proportional to the surface area of the extruded clay column; therefore, the mm ^{3} wear loss per m ^{2} area of clay column was chosen as the common basis, or wear coefficient, and it is hereinafter designated as y.

2. RELATION OF WEAR COEFFICIENT, PRESSURE, WEAR RESISTANCE COEFFICIENT OR SERVICE VALUE, AND RELATIVE WEAR RATE

The wear coefficients and corresponding extrusion pressures were plotted logarithmically for each die material of substantially uniform wear rate.[12]

The plots for the different materials were all straight lines of very nearly the same slope. The relation between wear coefficient and extrusion pressure is:

$$\log y = m.\ \log.\ p - \log.\ K$$

or

$$y = \frac{p^m}{K}$$

in which y is the wear coefficient; p is extrusion pressure; K is wear resistance coefficient, also relative service value, and is constant for a material of uniform wear, and m is constant for all of the materials.

For this particular mode of testing and for the given units adopted for y and p, K is a specific constant for a die material of uniform wear resistance and represents its ability to withstand abrasion; that is, its relative service value. The reciprocal of K represents relative wear rate (v); (see p. 505 and fig. 2).

The service value may be considered as the length of time the die operates or the length of clay column extruded under constant working conditions which produces a definite volume wear loss.

3. RELATIVE WEAR RESISTANCE

The data were obtained on from 8 to 18 tests for each material. The extrusion pressure of 25 kg/cm^2 (355.6 lb/in.^{2}) lies close to the mean extrusion pressures for the different materials tested. The wear losses expressed as y were therefore calculated at $p = 25$ kg/cm^2 and are shown for comparison in column 3 of table 3. It is seen that the y values vary from 45.46 for the brass to 0.0869 for a chromium-cobalt-tungsten alloy.

The values of the exponent m determined experimentally are shown in column 4. The lowest m value is 1.511 for cast iron no. 8 and the highest 1.577 for stainless steel no. 15. The average for all tests of uniformly wearing dies is 1.548. No satisfactory m value was obtained for the cast electrolytic copper, which proved to be somewhat spongy and wore unevenly.

The comparative service values K (wear resistance coefficients, column 5, table 3) were calculated on the assumption that $m = 1.548$ for all the materials. The lowest service value is shown by the brass, and that of the copper is evidently lower than otherwise would be the case because of its spongy structure. There is no uniform gradation in service values from the lowest to the highest. The stainless steels and cast irons are all grouped within service values from 21.56 to 27.01. The chromium tool steel dies range in service value from 38.26 to 147.8, which may primarily be due to differences in their heat treatments. There is a difference of 404.8 in service value between chromium tool steel no. 21 and chromium-molybdenum steel

[12] Dies of nitrided steel and of porcelain showed unequal wear with depth.

no. 3 and also a wide margin between no. 3 and the chromium-cobalt-tungsten alloys nos. 11, 12, and 13. The type composition of no. 11 is different from that of nos. 12 and 13. The two latter, although of the same type composition, show a difference of 272 in service value. This difference for the most part may be due to the different methods by which they were cast.

TABLE 3.—*Wear coefficients y at 25 kg/cm² extrusion pressure, experimental values for constants m, relative service values K when m=1.548; and Vicker's hardness numbers*

No.	Material	Experimental		Calculated	Vicker's [1] numbers
		y	*m*	*K*	
10	Brass	45.46	1.529	3.22	170
9	Copper	[2] 22.98		6.35	41
14	Stainless steel	6.789	1.546	21.56	170
8	Cast iron	6.394	1.511	22.91	165
15	Stainless steel	6.021	1.577	24.38	210
5	Cast iron	5.560	1.558	26.32	157
6	do	5.557	1.538	26.32	164
7	do	5.483	1.543	26.72	174
16	Stainless steel	5.407	1.558	27.01	323
19	Cr-tool steel	3.832	1.555	38.26	188
20	do	3.533	1.565	41.57	188
23	do	3.202	1.563	45.63	360
22	do	2.531	1.563	57.82	531
17	Carbon steel	2.037	1.538	72.05	605
21	Cr-tool steel	0.9906	1.575	147.8	750
3	Cr-Mo steel	.2650	1.546	552.6	699
11	Cr-Co-Wo alloy	.1057	1.524	1,377	604
13	do	.1034	1.543	1,401	641
12	do	.0869	1.531	1,673	687
4	Nitrided steel *K* decreased from 115.1 for the first test to 70.8 for the ninth test.				
12	Porcelain *K* decreased from 107.7 for the first test to 66.3 for the twelfth test.				

[1] Each Vicker's number is the average of 12 determinations.
[2] Calculated on the average wear loss *y*, average extrusion pressure *P*, and average *m* (1.548).

4. SERVICE VALUES COMPARED WITH VICKER'S NUMBERS

The Vicker's numbers [13] are given in the last column of table 3. No correlation exists between hardness numbers and service values for unlike materials. For instance, the brass has a service value of 3.22 and a hardness number of 170, while stainless steel no. 14 has the same hardness number and a service value of 21.56. However, there is in general a direct relation between hardness numbers and service values for like materials. This is observed in the cast irons nos. 5, 6, and 7, the stainless steels nos. 14, 15, and 16, the different heat-treated chromium tool steels nos. 19 to 23, inclusive, and the three cobalt-chromium-tungsten alloys nos. 11, 12, and 13. Alloy no. 12 has the highest service value, namely 1,673, with a hardness number of 687, whereas the chromium tool steel no. 21 heated to 1,650 F and hardened in air blast shows the highest hardness number (750) with a service value of only 147.8.

5. VARIABLE WEAR WITH DEPTH

(a) NITRIDED STEEL

Nine wear determinations were made on each of two duplicate nitrided steel dies (no. 4, table 1 and fig. 6). Successive tests for each die showed variable wear, although the results of corresponding tests

[13] Vicker's numbers were determined by engineering mechanics section, Bureau of Standards.

for the two dies showed approximate agreement. The wear resistance coefficient K was, therefore, calculated for each test. These values were plotted against corresponding depths of wear in millimeters as shown in figure 6.

No photomicrograph was made of the dies, but the course of the curve of figure 6 indicates the existence of three different layerlike parts to a depth of about 0.105 mm (0.00413 in.). From a depth of 0.005 mm (0.0002 in.) to approximately 0.04 mm (0.00157 in.) the K value decreases from about 116 to 67. The second portion lies

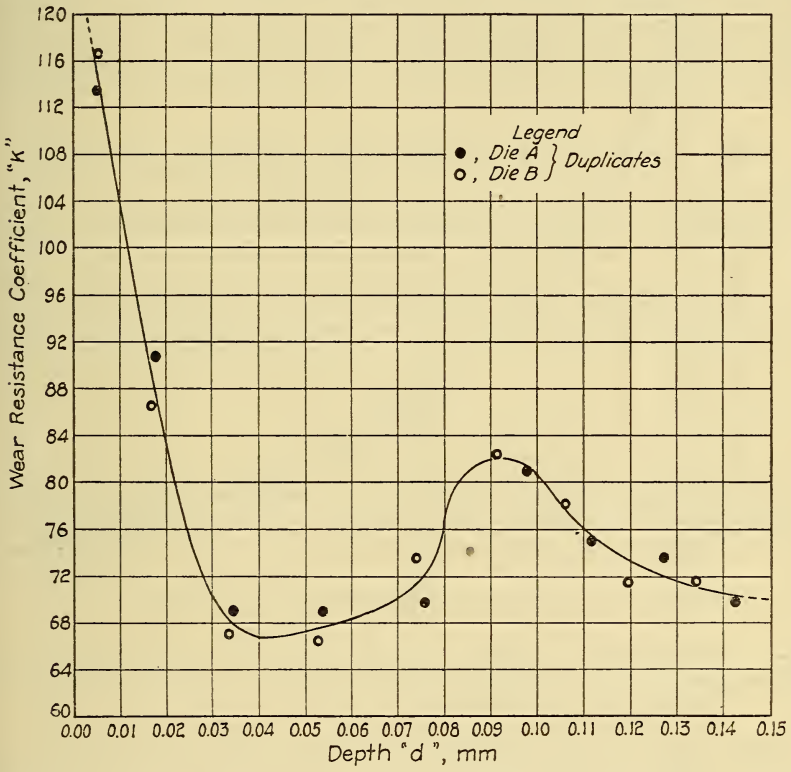

FIGURE 6.—*Relation between wear resistance coefficient and mm depth of abrasion for nitrided steel.*

between depths of near 0.04 to 0.075 mm (0.00157 to 0.00295 in.) in which the K value increases slightly. The third portion shows a sharp increase in K value to its maximum of 82 at a depth of approximately 0.093 mm (0.00366 in.) and beyond this depth the K value decreases.

At the end of the ninth test an average of 7,800 feet (2,377 m) of clay column had been produced for each die, equal in length to one from a brick machine which would yield approximately 38,400 side-cut face brick, or about a half-day's operation for an ordinary auger brick machine. This length of clay column had produced a wear depth of 0.14 mm (0.0055 in.), where the K value was approximately 70.78. Not all of the case had been removed, but the more wear-resistant part had disappeared and it is probable from the hardness numbers

at depths of 0.005 to 0.015 inch (0.127 to 0.381 mm) reported by Harder, Gow, and Willey [14] for a number of nitrided specimens that the K value would continue to decrease down to the depth of the untreated steel.

(b) PORCELAIN

The data obtained from 12 consecutive tests for each of the porcelain dies (no. 24, table 1 and fig. 7) showed an increasing rate of wear

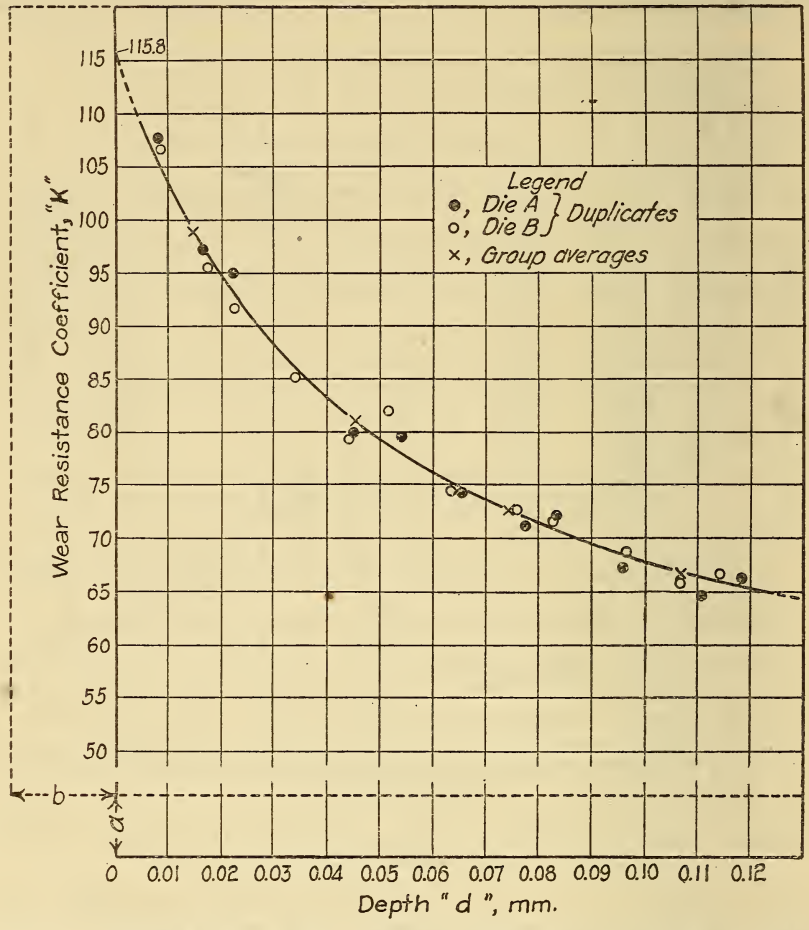

FIGURE 7.—*Relation between wear resistance coefficient and mm depth of abrasion for the porcelain.*

which appeared to approach a constant value, and corresponding tests of the dies showed reasonably close agreement. This increasing rate of wear was due to the so-called skin or hard outer portion of the porcelain which was evidently developed during the kiln treatment. The K value, calculated for each test, was plotted against depth in millimeters as shown in figure 7. Each of the 4 group averages represents the average of 3 consecutive duplicate tests.

[14] Trans. Am. Soc. Steel Treating, vol. 16, no. 5, p. 132, 1929.

The relation obtained between the K value and depth within the experimental limits is of the form:

$$(K-a)\ (d+b)=G$$

where K is wear resistance coefficient; d is depth, and a, b, and G are constants. Calculated on the values of the group averages, the values of the constants are approximately: $a=45.78$, $b=0.0462$, $G=3.235$.

The results obtained indicate that the K value decreases asymptotically with depth to some minimum value and that no break appears in the curve to indicate an abrupt change in the character of the hard outer portion of the porcelain. Theoretically, the minimum and maximum values of K for the porcelain are 45.78 and 115.8, respectively.

6. RELATIVE ABRADING INTENSITIES OF CLAYS NOS. 1 AND 2

Sixteen tests were made with clay no. 2 as the abrasive to obtain data for comparing its abrasive intensity with that of clay no. 1. These tests were made on chromium tool steel dies 21A and 21B previously tested for wear resistance to clay no. 1.

The data obtained for the wear losses (wear coefficient z) and the corresponding extrusion pressures p, when plotted logarithmically, showed the following relation:

$$z=\frac{p^{0.866}}{80.64}$$

while the equation obtained with clay no. 1 as the abrasive and the same dies gave the relation between wear coefficient y and extrusion pressure p as:

$$y=\frac{p^{1.575}}{160.5}$$

From these equations the expression $\frac{z}{y}=\frac{1.99}{p^{0.709}}$ is obtained from which the approximate relative abrasive intensities of the two abrasive mediums can be determined at any pressure within the limits covered by the tests.

In figure 8 the numerical y and z values are plotted against corresponding extrusion pressures which ranged from 17 to 29 kg/cm^2, (214.8 to 412.4 lb/in.^{2}). At the former pressure, $\frac{z}{y}=\frac{1}{3.75}$ and at the latter, $\frac{z}{y}=\frac{1}{5.47}$.

V. SUMMARY AND CONCLUSIONS

A study was made of dies of 20 metals and alloys and dies of porcelain to determine their relative resistances to wear by a plastic clay-sand mixture termed clay no. 1. The approximate angle of constant wear rate was determined for the specific dies used in the study. In addition, tests were made on one die material to determine the relative abrasive intensities of a plastic porcelain body (clay no. 2) and clay no. 1. A constant volume of the abrasive material in the stiff mud condition was extruded from the dies at a constant volume rate and their wear losses determined. Vicker's hardness numbers of the specimens were also determined.

Analysis of the data warrants presentation of the following results and conclusions:

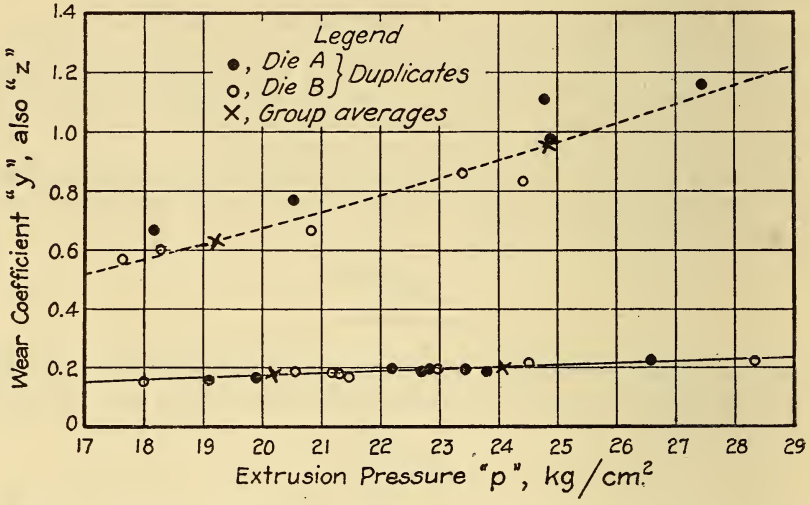

FIGURE 8.—*Relation between wear coefficient y and extrusion pressure p for tests with clay no. 1 (dotted line) and relation between wear coefficient z and extrusion pressure for tests with clay no. 2 (solid line).*

Tests made on chromium tool steel dies 21*A* and 21*B*.

1. The relative service values ranged from 3.22 for a brass to 1673 for a cobalt-chromium-tungsten alloy.

2. Tests of different dies of a chromium tool steel which had received five different heat treatments yielded service values from 38.26 for annealed dies to 147.8 for dies heated to 1,650 F and hardened in air blast.

3. Under constant working conditions, dies with cylindrical orifices wear toward a tapered orifice, with which orifice a wear rate constant within the limits of the tests was obtained. The relation between wear rate and time for a die in wearing from a cylindrical orifice to a taper of "constant wear rate" is of the character:

$$(a+u)\ (b-v)=R$$

in which v is wear rate; u is time equivalent; and a, b, and R are constants.

4. The relation between wear loss and extrusion pressure is of the character:

$$y=\frac{p^m}{K}$$

in which y is "wear coefficient"; p is extrusion pressure; m is constant for all materials; and K is "wear resistance coefficient", a specific constant for a die material of uniform wear resistance and represents its ability to withstand abrasion; that is, its "relative service value."

5. No correlation between Vicker's hardness numbers and service values was obtained for dies of unlike materials, but there is in general a direct relation for dies made of materials of the same character.

6. The wear resistance of nitrided steel dies decreased, increased, then decreased as layers at different depths of the case were removed. The relative wear resistence value for the first test was 116, while that for the ninth was 71 at a depth of 0.14 mm (0.00551 inch).

7. Within the experimental limits the wear resistance of porcelain dies decreases with depth asymptotically according to the equation:

$$(K-a)\ (d+b)=G$$

in which K is wear resistance coefficient; d is depth; and a, b, and G are constants. The numerical values obtained for the constants were: $a=45.78$, $b=0.0462$, and $G=3.235$.

8. Comparison of the relative abrasive intensities of a plastic porcelain body and a plastic clay-sand mixture on dies of one material was found to be $\frac{z}{y}=\frac{1.987}{p^{0.708}}$, in which z is wear coefficient when using the plastic porcelain body (clay no. 2) as the abrasive, y is wear coefficient when using the plastic clay-sand mixture (clay no. 1) as the abrasive, and p the extrusion pressure.

Washington, January 13, 1934.

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